6.2 **Precipitation Processes Derived from TRMM Satellite Data, Cloud Resolving Model and Field Campaigns**

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1. INTRODUCTION

Rainfall is a key link in the hydrologic cycle and is a primary heat source for the atmosphere. The vertical distribution of latent-heat release, which is accompanied by rainfall, modulates the large-scale circulations of the tropics and in turn can impact midlatitude weather. This latent heat release is a consequence of phase changes between vapor, liquid, and solid water. Present large-scale weather and climate models can simulate cloud latent heat release only crudely, thus reducing their confidence in predictions on both global and regional scales.

In this paper, NASA Tropical Rainfall Measuring Mission (TRMM) precipitation radar (PR) derived rainfall information and the Goddard Convective and Stratiform Heating (CSH) algorithm are used to estimate the four-dimensional structure of global monthly latent heating and rainfall profiles over the global tropics from December 1997 to October 2000. Rainfall, latent heating and radar reflectivity structures between ENSO (1997-1998 winter) and non-ENSO (1998-1999 winter) periods are examined and compared. The seasonal variation of heating over various geographic locations (i.e. Indian ocean vs west Pacific; Africa vs S. America) are also analyzed. In addition, the relationship between rainfall, latent heating (maximum heating level), radar reflectivity and SST are examined.

2. Goddard Convective and Stratiform Heating (CSH) algorithm

Diagnostic budget (Houze, 1982; Johnson, 1984) and cloud modeling studies (see a review by Tao, 2001) have shown that the distribution of heating in the anvil region of tropical mesoscale cloud systems is considerably different from the vertical profile of heating in the convective region. Generally, evaporative cooling in the lower troposphere is dominant in the stratiform region in all simulated convective systems. On the other hand, condensation/deposition heating is dominant in the convective region in these convective systems. Based on these findings, a convective-stratiform heating algorithm has been developed (Tao *et al.* 1993). There are many sets of normalized heating profiles; each set has a convective profile and a stratiform profile simulated by cloud resolving models or diagnosed from budget calculations. Each set represents different system organizations as well as various geographic locations. Figure 1 shows the schematic diagram of the CSH algorithm.

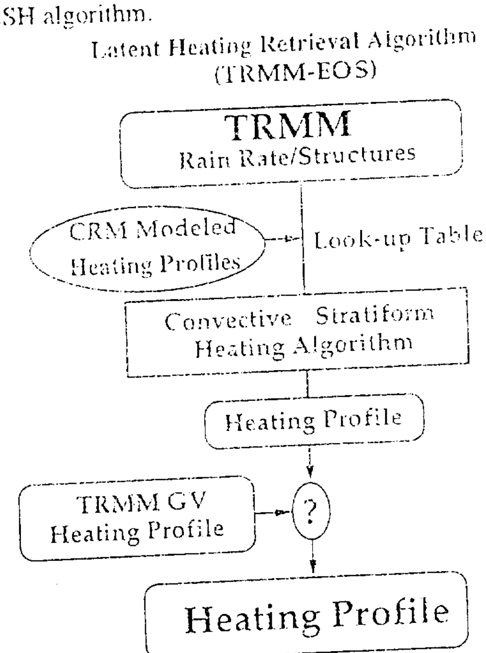

Fig. 1 Diagram showing the procedure for deriving the latent heating profile from the convective-stratiform heating (CSH) algorithm. The heating profile (Q_1) is normalized by the surface precipitation rate (P_0).

Vertical profiles of latent heat release and their retrieval using the CSH algorithm associated with several TOGA COARE convective active periods are examined by Tao *et al.* (2000). The inputs for the CSH algorithm are SSM/I (synthetic TMI) and Radar (synthetic TRMM PR) derived rainfall and stratiform amount. Results indicated that temporal variability of CSH algorithm retrieved latent heating profiles using radar estimated rainfall and stratiform amount is in good agreement with that diagnostically determined. However, less rainfall and a smaller stratiform percentage estimated by radar resulted in weaker

(underestimated) latent heating profiles and lower maximum latent heating levels compared to those determined diagnostically. Rainfall information from SSM/I can not retrieve individual convective events due to poor temporal sampling. Time averaged heating profiles derived from SSM/I, however, are not in bad agreement with those derived by soundings.

Tao *et at.* (2001) used the TRMM rainfall information to estimate the four dimensional latent heating structure over the global tropics for one month (February 1998). The latent heating profiles derived from the CSH algorithm were compared to those derived from two other different heating algorithms, the Goddard Profiling (GPROF) heating, and the Hydrometeor heating (HH). The horizontal distribution or patterns of latent heat release from the three different heating retrieval methods are quite similar. They all can identify the areas of major convective activity [i.e., a well defined Intertropical Convergence Zone (ITCZ) in the Pacific, a distinct South Pacific Convergence Zone (SPCZ)] in the global tropics. The magnitude of their estimated latent heating release is also in good agreement with each other and with those determined from diagnostic budget studies. However, the major difference among these three heating retrieval algorithms is the altitude of the maximum heating level. The CSH algorithm estimated heating profiles only show one maximum heating level, and the level varies between convective activity from various geographic locations. These features are in good agreement with diagnostic budget studies.

3. TRMM PR Rainfall Data

The TRMM Precipitation Radar (PR) operates at a frequency 13.8 GHz. This is a moderately attenuating frequency so that one of the major objectives of the PR algorithms is to estimate and correct for the path attenuation. Because the PR is a single-wavelength, single-polarization, non-Doppler radar, there are only a few methods available to estimate rainfall. These include the Hitschfeld-Bordan (HB) method, the surface reference technique or SRT, a "hybrid" of these, and the mirror-image technique. The rain rate estimation algorithm uses a hybrid of the Hitschfeld-Bordan method and the SRT to correct for attenuation and derive an estimate of the range profile of the radar reflectivity factor, dBZ. The rain rate profile is then calculated from the dBZ profile and an appropriate Z-R relationship. The algorithm also includes surface clutter rejection and an attempt to correct for effects of non-uniform beamfilling.

Convective-stratiform classification of the rain is based on a combination of the vertical and horizontal structure of the radar reflectivity field. The vertical profile is checked for the presence of a bright-band (melting layer) by considering the behavior of the second derivative of the radar range profile. Unless the maximum dBZ exceeds a threshold, the presence of a well-defined bright-band is used to indicate stratiform rain. In cases where a clearly defined melting layer is absent, the horizontal rain structure is examined by means of a modified version of an algorithm designed for the analysis of ground-based radar data.

Statistics of the instantaneous, high-resolution rain rates are compiled on a monthly basis over 0.5^{o} x 0.5^{o} latitude-longitude grids. Near-surface rain rates and the rain rates at 3 altitude levels are stored according to rain type. The statistics include means, standard deviations and histograms of the rain rate, radar reflectivity factors, bright-band and storm heights. Please see Tao *et al.* (2001) for a brief description of the PR rainfall algorithms and convective stratiform separation.

4. Results

Figure 2 shows three yearly mean latent heating at three different altitudes (2, 5 and 8 km) over the global tropics from the CSH algorithm using PR derived rainfall products and latent heating profiles in the look-up table representing general tropical oceanic and land regions (obtained by averaging profiles from the look-up table). The horizontal distribution pattern of the CSH estimated latent heating structures is very similar to the pattern of surface rainfall (not shown), especially at middle and upper levels. For example, a well defined ITCZ in the east and central Pacific and in the Atlantic Ocean, a distinct S. Pacific Convergence Zone (SPCZ), and broad areas of precipitation events spread over the continental regions, are present. Also, strong latent heat release (5 K/day or greater) in the middle and upper troposphere is always associated with heavier surface precipitation. Heating in the upper troposphere over the Pacific and Indian Oceans covers a much broader area than the heating over Africa, S. America and the Atlantic Ocean. The differential heating distribution between land and ocean in the upper troposphere could generate strong horizontal gradients in the thermodynamic fields and interact with the global circulation.

One interesting result from Fig. 2 is the relatively weak heating and cooling (-1 to 1 K/day) at the 2 km level over the Pacific Ocean. This result may be due to the fact that the moisture content is high over the Pacific ocean. Cooling by evaporation of raindrops in the lower troposphere could be weak over moist areas. Another possibility is that strong heating and cooling associated with the life cycle of many convective systems or seasons may cancel each other.

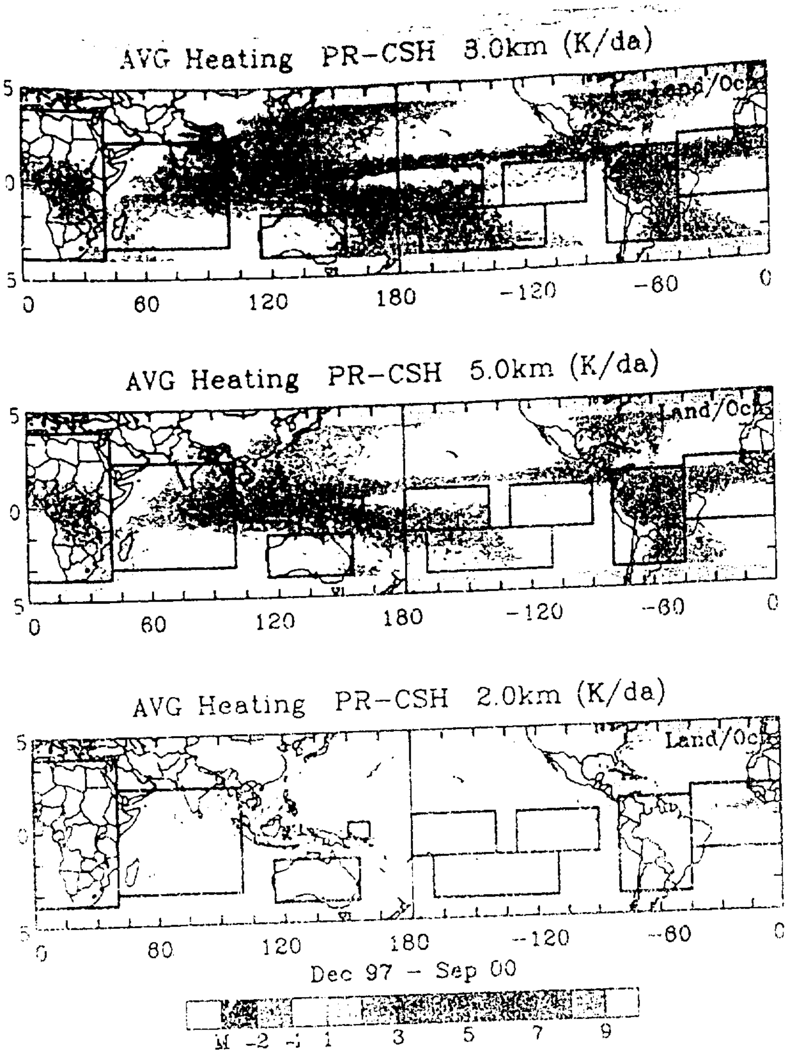

Fig. 2 Three year mean latent heating profiles at (a) 8, (b) 5 and (c) 2 km (above ground level, AGL) over the global tropics. Latent heating profiles representing tropical oceanic and general land regions from the CSH look-up table (LUT) were used.

Time (monthly) series of latent heating profiles over the tropics and their deviations (from the mean) are shown in Fig. 3. The level of maximum heating is at 7.5 km. The variation of the maximum heating level as well as the magnitude are quite small (Fig. 3a). However, there are cold anomalies during ENSO (1997-1998 winter) and warm anomalies during non-ENSO (1998-1999 winter) periods. These features are due to the fact that the PR observed a higher percentage of stratiform precipitation during the ENSO period which is conducive to retrieving stronger low level cooling compared to the non-ENSO period.

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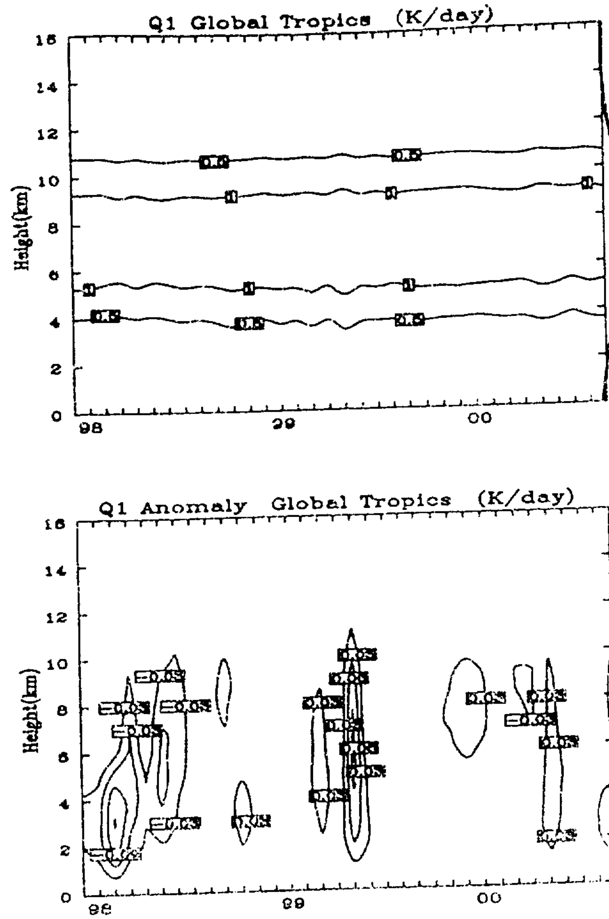

Fig. 3 (a) Time evolution of global mean latent heating and (b) its deviation derived from the CSH heating algorithm.

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